Geotechnical Investigation and Rock Characterization for the East Side Access Project's Manhattan Segment

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GEOTECHNICAL INVESTIGATION AND ROCK CHARACTERIZATION FOR THE EAST SIDE ACCESS PROJECT'S MANHATTAN SEGMENT

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ABSTRACT

The East Side Access Project to connect the Long Island Railroad to New York's Grand Central Terminal on the east side of Manhattan will be one of the largest tunneling projects ever undertaken in New York. A series of tunnels and caverns will be excavated in rock to connect the existing 63rd Street tunnels to twin three-level caverns beneath Grand Central Terminal. The site investigation for the Manhattan Segment comprised archive searches, rock exposure mapping, geophysical surveys, test borings in soil and rock, in-situ testing, groundwater monitoring, and laboratory testing of soil, water and rock. Approximately 200 borings have been drilled along the alignment from the existing tunnels at 63rd Street and 2nd Avenue to 38th Street and Park Avenue. Specialized investigation methods included oriented core borings and televiewer surveys to determine the dip and dip direction of the discontinuities, drilling at angles to intercept specific geological features such as faults, shear zones, geological markers and altered rock. Extensive local rock exposure mapping was carried out to correlate the core orientation data thereby establishing a specific structural model for the project. The data have been interpreted to provide a geological model for the Manhattan segment of the project. This paper focuses on the philosophy and description of the methods of geological characterization undertaken, presents a comprehensive discontinuity reference and engineering properties of the rock mass.

INTRODUCTION

The East Side Access Project (ESA) is a major capital construction project to be carried out by the Metropolitan Transit Authority (MTA) in conjunction with the Long Island Rail Road (LIRR). The project will provide Long Island commuters with direct access to Manhattan's Grand Central Terminal (GCT), which will help relieve congestion at Penn Station and provide direct access to the East Side of Manhattan. The connection is to be accomplished by providing a new rail line between the Sunnyside Yard in Queens and the GCT in Manhattan using the lower level of the existing 63rd Street Tunnel under the East River and new tunnels in Queens and Manhattan (Fig. 1).

The Manhattan segment of the East Side Access project is situated under mid-town Manhattan's densely populated residential and business district from East 63rd Street and Second Avenue to the intersection of Park Avenue and East 38th Street. The Manhattan Segment consists of three major underground construction elements (Fig. 2):

- Manhattan Tunnels including the 55th Street ventilation structure

- GCT Caverns, tunnels and shafts connecting the new LIRR terminal to the existing GCT Madison Concourse and the 44th Street ventilation structure

- Tail track tunnels and caverns and 38th Street ventilation structure.

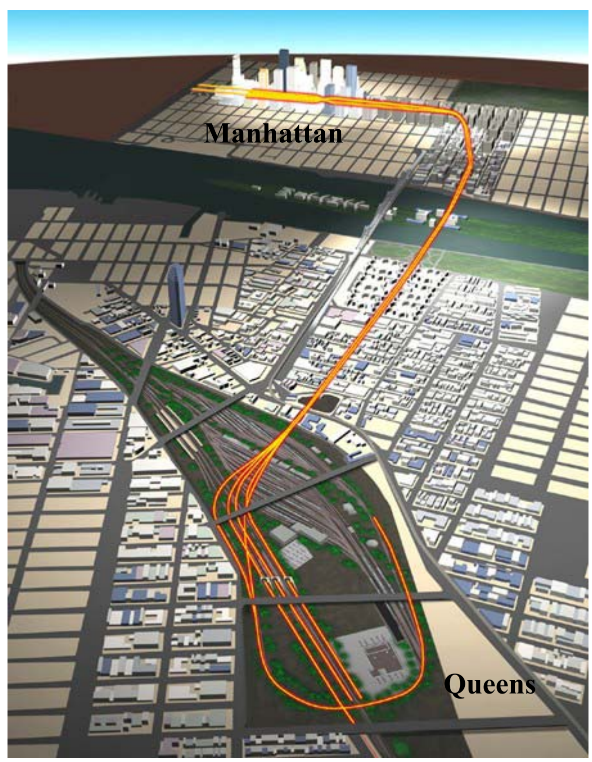

Fig. 1. Location Plan of the East Side Access Project.

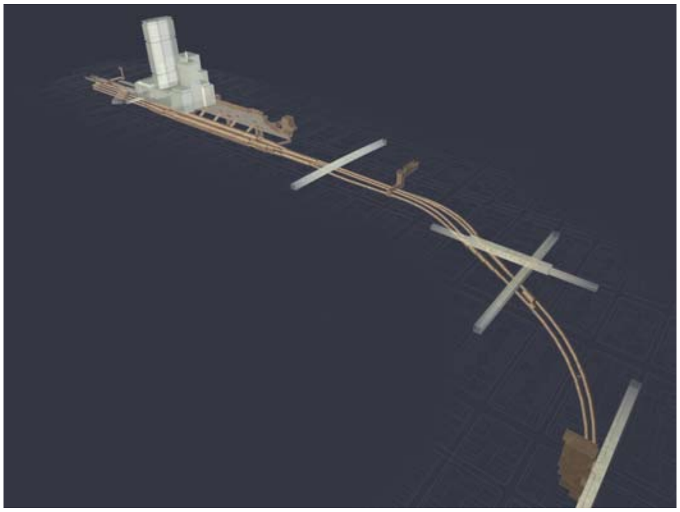

Fig. 2. ManhattanTunnels.

The Manhattan Segment tunnels and caverns will be built under various existing operating New York City Transit (NYCT) subway lines and Metro North Railroad (MNR) lines, and the GCT which accommodate numerous foundations of high-rise buildings.

A very comprehensive geotechnical investigation program was undertaken to evaluate geologic structure and engineering properties of the rock mass that are required to meet the challenges during site investigation, tunnel and cavern design, and excavation and support installation.

GEOTECHNICAL INVESTIGATION CHALLENGES

Physical challenges include the built environment in densely developed Manhattan island, including historic residential districts, high-rise condominium and commercial buildings, fully developed infrastructure with numerous continuously operated transit and railroad tunnels, buildings with deep basements, high-rise building foundations within the footprint of the lower level of Grand Central Terminal (GCT) station and the historic GCT station complex with numerous commercial outlets and access ways to various buildings over and around GCT. The proposed ESA station caverns will be constructed below the existing two-level GCT, with a rock cover of approximately 35 feet between the existing GCT lower and the roof of the proposed cavern.

Excavation of the caverns and tunnels, and the subsequent redistribution of stresses within the surrounding and overlying rock cause deformation of the rock, the magnitude of which depends upon the ground conditions encountered. Therefore, a primary objective of the site investigation was not only to identify and characterize the ground conditions but also to assess the rock mass deformation and changes in groundwater flow regimes and their effect on the overlying and adjacent tunnels, viaducts and high-rise structures. The general alignment and sizes and shapes of the underground excavations were controlled by the operational requirements of the MTA. The geotechnical investigation therefore sought to achieve an understanding of the rock structure in order to adapt the ground conditions to the tunnels and caverns with due regard to the proximity of existing structures. In some cases, however, ground conditions dictated the location of certain structures, while remaining within the boundaries of operational requirements. The major objectives of the geotechnical investigation were to achieve the following:

- Determination of the locations, shapes and sizes of the various underground openings with regard to railroad operational requirements and constraints.

- Determination of underground opening design parameters based upon excavation size, shape, use, and proximity to adjacent and overlying structures, including, loads to be resisted by the structures, groundwater control and waterproofing requirements, stability assessment and initial support design, final liner design and the effects on adjacent and overlying structures.

- Determination of construction methods, sequences, and progress rates, with due regard to adjacent and overlying structures and quality of life issues.

- Determination of specific problems to be expected during construction and operation, either due to natural ground conditions or due to the proximity of adjacent and overlying structures, and, so far as practicable, their extent and expected locations.

The metamorphic rock underlying Manhattan, consisting of foliated schist and gneiss, is known to be highly variable, ranging from very hard competent rock to very soft and partially disintegrated material (fault breccia and shear zones). Significant tunneling stability problems have been recorded in the past by many authors (Ziegler and Loshinsky, 1981; Loshinsky, 1983; McCusker and Dietl, 1974; Almeraris, et. al., 1985; Guertin and Plotkin, 1979; Werbin, 1916; Lavis, 1914; Interborough Rapid Transit Company, 1904). Therefore, driving tunnels or making open cut excavations in this type of rock under heavily traveled streets, high-rise and residential buildings, subway and other railroad lines, and various utilities, is known to require great care.

Since the geotechnical investigation provides direct evidence of only a miniscule portion of the rock to be penetrated by the underground openings, it was deemed most important to search for patterns in the geotechnical data obtained in order to predict the nature and variability of the ground conditions. In the jointed and mostly competent rock found under Manhattan, the major task in geotechnical investigation was to identify and quantify the variations in jointing geometry, intensity and character, and the associated groundwater inflows. This pattern identification was directed towards achieving the goal of subdividing the alignment into several “rock zones” based upon the complex association of rock mass properties, stress conditions, and groundwater regimes. Such classification allowed the selection and assessment of construction methods, estimation of progress rates, the design of classes of initial rock support, and the estimation of loading conditions for the design of the final liner. Superimposed over this was the requirement of minimizing or eliminating any effect on adjacent and overlying structures. This type of classification of the rock mass, construction methods and support classes ultimately lead to a realistic construction cost estimate.

Technical challenges of the site investigation included:

- Assessment of general geologic conditions, including rock types, degrees of weathering and strength assessment.

- Discontinuity characterization and investigation of specific features such as foliation, folding and faulting, shear zones, joint orientation, and spacing.

- Classification of the rock mass conditions for rock support design.

- Groundwater conditions assessment and inflow as they relate to water control during excavation and service, and water proofing requirements.

- Determination of engineering properties of rock materials and discontinuities for stability assessment (numerical analysis) of the tunnel excavations and cavern construction, and effects on adjacent structures.

- Engineering properties specific to construction methods, such as parameters for TBM drillability assessment.

Physical and logistical challenges that were faced during this site investigation included drilling underground from inside active railroad and transit tunnels and GCT during nighttime windows, no access to building basements, and the presence of numerous utilities, various smaller tunnels (steam tunnel, cross passageway, etc.) and numerous obstructions within the railroad tunnels and GCT. The drilling required significant coordination with railroad and transit agencies and enforcement of stringent health and safety plans. Drilling from the streets had its own problems. Because of the importance of the area, permits were not generally given for drilling through traffic lanes on Park Avenue and during weekdays. All of the drilling was done through sidewalks or curb lanes. However, due to dense underground utilities and underground vaults, it was often impossible to find a clear six-inch opening for a borehole. A very strict utility clearance procedure was followed during drilling. Many borings were abandoned after numerous attempts.

GEOTECHNICAL INVESTIGATION APPROACH

In order to meet the above challenges, the following sequence of site investigation was followed:

- Desktop study of archive data from accessible sources including geological maps, memoirs and monographs

- Two phases of actual geotechnical investigation, in increasing degree of detail and progressively more focused towards the preferred alignment and construction options.

- Further investigation, as required during the construction phases of the project.

The actual methods used for the geotechnical investigation included the following:

Drilling

A total of 191 borings were drilled, including vertical boreholes, inclined boreholes in shear zones and under inaccessible areas, oriented cores, large diameter boreholes (for direct shear testing on rock joints) and laboratory testing of anisotropic properties. In areas where vertical and inclined drilling could not be performed from the street or from underground space, horizontal directional drilling was contemplated; however, it was considered uneconomical under difficult Manhattan access conditions.

Rock Mapping

The two-track level below GCT was constructed by drilling and blasting about 50 years ago. Parts of the perimeter excavation walls are still exposed. Rock mapping was performed in areas of west wall, south wall in the lower level GCT, and a substation located under the GCT. The discontinuities mapped were compared and correlated with data obtained from borehole televiewer logging and borehole oriented cores. The rock exposed at the stub end of the existing 63rd Street subway tunnel was mapped by stereophotogrammetry.

In Situ Testing

Various in situ tests were performed to generate rock properties. The methods used were hydrofracturing of borehole walls, televiewer mapping of borehole walls, borehole dilatometer tests, single and double packer water permeability tests within boreholes, and geophysical tests in areas of old stream beds identified along the tunnel alignment. These areas were identified as potential shear zones and confirmed by the investigation. Vibration transmittivity of rock was measured by hammer dropping through boreholes and train passages through railroad tunnels as sources of vibration.

Laboratory Testing

Laboratory testing included petrographic thin section analysis, point load, uniaxial compressive and tensile strength tests along and across joints for anisotropy, modulus tests, seismic velocity tests, direct shear tests on rock joints, suites of TBM performance tests including abrasivity and special tests for roadheader performance.

RESULTS OF THE GEOTECHNICAL INVESTIGATION

The results of the site investigation provided the following:

- General geologic conditions along the alignment.

- Identification of discontinuities due to foliation and folding.

- Discontinuity geometry, intensity, and characteristics.

- Identification of special features such as faults and shear zones.

- Rock mass characterization for rock support design during construction and final liner design.

- Groundwater conditions for control during excavation, waterproofing design, and drainage design.

- Engineering properties of rock (intact and jointed rock mass, strength along and across joints, rock modulus, and friction along joints) that was used in continuum and discrete numerical model /analysis of excavations. These engineering properties were also used for deformation analysis and for assessing the effects of construction on structures above and adjacent to excavation.

- Engineering properties specific to construction method such as TBM drillability and roadheader performance.

A brief description of the rock, structural discontinuities and rock characteristics along the project alignment is provided below.

GEOLOGIC SETTING

New York City is characterized by a complex geological structure. The five Boroughs overly three physiographic units, namely, the New England Upland on the northwest, the Triassic Lowland on the southwest, and the Atlantic Coastal Plain to the southeast. The rocks underlying Manhattan, the Bronx, and a part of Staten Island belong to the New England Upland, and are locally known as the Manhattan Prong. The basic bedrock in the Manhattan Prong is composed of metamorphic rocks that are Proterozoic to Ordovician in age (Baskerville, 1982; Baskerville, 1994). The rocks include the Fordham Gneiss, described as a basement complex (Hall, 1968), which is overlain by the Inwood Marble and the Manhattan Schist. Contemporary with the Manhattan Formation rocks are the Hartland Formation schist and gneiss (of Lower Cambrian to Middle Ordovician age), which originated as sedimentary and volcanic deposits in an island arc environment to the east of the Manhattan Formation. During the Taconian Orogeny, which occurred about 450 million years ago, the proto-North American continent collided with the island arc terrain, juxtaposing Manhattan Formation rocks with Hartland Formation rocks along a major regional NNE-SSW trending thrust fault known as Cameron's Line (Isachsen, 1991). As part of this tectonic event, fluid-rich granitic melts (pegmatites and related granitic rocks) derived from saturated ocean basin sediments, intruded along dikes and sills into the schists and gneisses. The rocks were subsequently tightly folded and metamorphosed (Isachsen, et al., 1991), resulting in the major regional NNE-SSW structural trend of the Manhattan Prong. During the Acadian Orogeny (350 m.y. bp), the region was again subjected to tectonic deformation, causing fractures, faults and joints trending WNW-ESE (Shah, et al., 1998). The Manhattanville (125th Street) Fault and similar WNW-ESE trending faults and shear zones recorded at many places within Manhattan Island are results of the Acadian deformation.

The rocks under Manhattan have historically been included together as a single unit called the Manhattan Schist. It has recently been suggested, however, that the Hartland Formation may overlie the Manhattan Schist in a thrust contact, which covers the greater part of Manhattan (Baskerville, 1989; Sanders and Merguerian, 1997). Therefore, most bedrock in the project area has recently been mapped as Hartland Formation.

The main rock types in the project area are metamorphic, dominated by schist and pegmatite. The essential minerals are muscovite, biotite, quartz, plagioclase, microcline and orthoclase feldspar. Garnet is the principal accessory mineral. In places, the schist grades into a granofels (a fine to medium grained equigranular metamorphic rock in which there is very little discernible foliation or banding). Amphibolite, consisting mainly of hornblende, plagioclase and biotite, is intercalated with the schists, and lies parallel to the foliation. Also occurring within the rock are layers of probable igneous origin, which vary from medium grained granite to coarse-grained pegmatite. These granitic layers commonly occur parallel to foliation; however, some intrusions are observed as dikes cutting across foliation. The mineral composition varies from true granite, containing orthoclase and plagioclase feldspar, quartz, biotite, and muscovite, to nearly pure quartz veins.

The most prominent fold phase developed the main regional macroscopic antiformal (F2) structure in Manhattan Island. The main cleavage/schistosity/foliation in the area (S2) show North to North 35^{o} East trend and plunge at low to high angles to either NW-SW or towards NE-SE according to the orientation of respective attitude of beds due to folding (Shah, et. al., 1998; Baskerville, 1989; Sanders and Merguerian, 1997).

The overburden deposits above the bedrock vary substantially in depth. In the Central Park region, the soil cover is relatively thin and increases southward toward lower Manhattan. The soils generally consist of glacial till, modified glacial drift, sands and gravels, some glacial lakebed silts and clays, and artificial fills. Water may be present in these soils; however; groundwater recharge by infiltration in Manhattan is relatively small.

The location of old stream channels, exposed rock and marshland are illustrated in historical documents (Viele, 1874). The stream channels are postulated to be influenced by glacial activity exploiting weaknesses in the rock but the effects may be masked by glacial till in places. Old streambeds have been identified along the tunnel alignment in the vicinity of 54th to 55th Streets, 58th to 59th Streets, and between 60th and 61st Streets. These areas were identified as potential shear zones and confirmed by the investigation.

STRUCTURAL DISCONTINUITIES

Discontinuities in the rock mass are the metamorphic fabric and joints caused by tectonic activity and granitization. All discontinuities exhibit a wide range of spacing values, which is typical of a rock mass that has undergone several phases of deformation. Joint clustering, defined as relatively closely spaced discontinuities in a given joint set, is another consequence of this tectonic disturbance.

Four dominant Joint Sets has been identified in the rock mass at the project site from geological mapping of the exposed rock, oriented core borings, and historical data. The most prominent joint set is one that is parallel to the plane of weakness formed by foliation and is termed Set 1. Set 2 is a steeply dipping joint set generally striking at high angles to foliation. Set 3 is a joint set that has the same strike direction as the foliation joints (Set 1) but dips in a direction opposite to foliation, and has been termed a conjugate to foliation. Set 4 joints also strike at generally high angles to foliation and are divided into two categories, 4 Low (shallow dipping) and 4 High (steeply dipping), according to their dip directions.

The data indicate substantial variation in both dip angles and dip directions for the four joint sets. The *entire range* of the observed variations is summarized in Table 1. From 38th Street to the north of GCT (to south of 53rd Street), the dip of the foliation joints (Set 1) is *typically* west to southwest. From 52nd to 56th Street the dip direction is *typically* south. North and east of 57th there is intense folding and faulting that produces a highly variable dip direction until approximately 62nd Street where the dip direction is to the East. Set 1 foliation joints are typically planar to undulating and rough.

Table 1. Discontinuity Attitudes along the ESA Alignment

ESA Alignment from 38th Street to south of 53rd Street				
Set No.	Dip Angle (degrees)		Dip Direction (degrees)	
	Range	Mean	Range	Mean
1	10 to 60	35	120 to 335	230
2	60 to 90	80	145 to 245	200
3	15 to 60	35	10 to 140	60
4L	5 to 40	25	265 to 360	300
4H	65 to 85	75	290 to 325	310
ESA Alignment from 55th Street to 63rd Street & Second Ave.				
1	5 to 75	25	0 to 360	150
2	60 to 90	70	95 to 290	175
3	10 to 80	40	200 to 55*	330
4L	10 to 40	20	335 to 10*	355
4H	55 to 85	70	245 to 35*	325
* clockwise from 200 degrees				

The Set 2 cross fabric joints are *typically* steeply dipping southeast to the southwest. The Set 2 joints display welding, healing, infill, open aperture, and coating. They are typically undulating, rough to very rough with rare infill of sand and clay and surface staining by iron oxide, particularly close to shear zones and in areas of more intense pegmatite formation. They are more closely spaced near the top of rock and close to previous excavations where they occur in clusters with a relatively closer spacing.

The Set 3 joints are conjugate to the foliation joints, *typically* dipping to the east beneath Park Avenue and varying in association with the folding and faulting east of Park Avenue. These are a fresh, closed set, typically undulating and rough to very rough with no infill.

The Set 4 joints occur in clusters with a wide variation of dip direction typically to the NW. The dip angle has been subdivided into shallow (4L) or steep (4H) groups and alteration and decomposition appears to be characteristic.

For illustration purposes, Fig. 3 shows a photograph of the exposed rock face of the south wall in GCT lower level. Rock features include foliation and foliation joints dipping 40°-60° towards the west.

Fig. 3. Photograph of GCT south wall showing vertical and horizontal mapping gridlines.

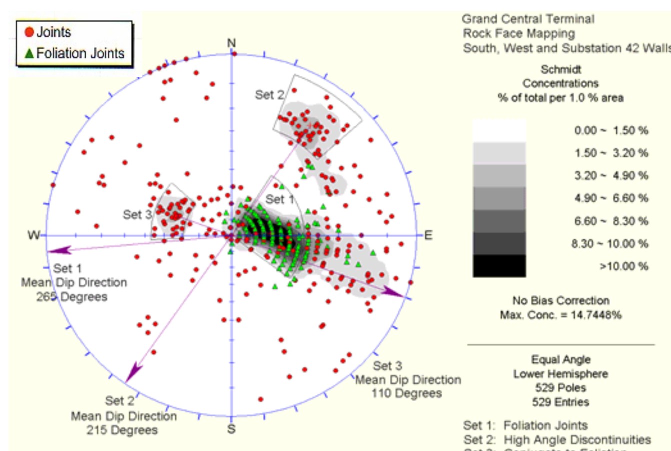

Fig. 4. Dips plot-Schmidt concentrations all joint and foliation data – south wall GCT

A stereographic pole plot of dip angles and dip directions of foliation and foliation joints generated using the "DIPS" software (Rockscience, 1998) is shown on Fig. 4. The discontinuity mapping conducted along the south wall and the west wall of GCT provided preliminary information regarding the jointing characteristics of the Manhattan rock. Joint Sets 1, 2 and 3, which were identified by Schmidt Concentrations of data points represented in "DIPS" software plots, were found to be consistent with the results from Borehole Televiewer Surveys conducted in boreholes along the alignment and with Manhattan joint set data published in the literature (as reported in Cording and Mahar, 1974).

GEOLOGIC ZONES

The Manhattan Segment has been subdivided into the following characteristic rock zones based on observed features, as shown on Fig. 5 (Snee, et. al., 2003).

Third Avenue to Second Avenue in the vicinity of 63rd Street

The rock types are foliated garnetiferous gneiss and schistose gneiss, with approximately 10% granofels. The rock mass has moderately to very widely spaced joints, widely spaced clusters of closely spaced joints, very widely spaced thin seams of moderately to highly weathered rock and very widely spaced micro-shears.

58th Street and Park Avenue to Third Avenue and 63rd Street.

The rock types are foliated garnetiferous gneiss and schistose gneiss, with approximately 5% granofels and less than 5% amphibolite. The amphibolite occurs parallel to foliation in layers up to 3 feet thick and is friable to decomposed. The rock is characterized by alteration, folding and dislocation.

Park Avenue between 57th Street and 58th Street.

A major shear zone east of Park Avenue intersects the project alignment between 57th and 58th Street. The general trend of the shear zone is NNW. The effects of shearing are identified in localized areas of the adjacent zones. The shearing and folding has created a complex and variable discontinuity system. The boundary of the shear zone is transitional and there are smaller scale shears and discontinuities with slickensides beyond the zone.

The complexity of the shearing has created commingling of the rock types. Tectonic processes have caused portions of the original rock to be sheared, brecciated and rehealed, forming cataclasite in a mylonite matrix. There is a high proportion of pegmatite in this zone.

In addition, there is a high proportion of very strong granofels. The rock surface has been incised by surface water along the shear zone due to its lower resistance to erosion. There is penetrative decomposition up to 15 feet thick below estimated top of rock demonstrating that the rock mass has a greater permeability and lower durability in this zone in comparison to the rock mass in adjacent zones. The rock changes with depth from decomposed to slightly weathered. There are alteration effects of decomposition, dissolution and mineralization.

Park Avenue between 54th Street to 57th Street.

This zone comprises garnetiferous schist, gneiss and granofels, a significant thickness of amphibolite in the vicinity of East 55th Street and a major 10-foot to 15-foot thick pegmatite dipping to the west across Park Avenue. The rock mass includes few open, infilled and slickensided fractures. The joints are closely to moderately and moderately to widely spaced but there are distinct sub domains of lower quality rock, characterized by clusters of very closely spaced fractures and persistent steeply dipping infilled fractures.

Park Avenue at 54th Street

This is a shear zone postulated to cross the tunnel alignment with an approximate E-W trend. The joints are typically closely to moderately spaced but with distinct clusters up to 10 ft thick of very broken rock, healed breccia (cataclasite), mylonite and, slickensided joints.

Park Avenue between 51st Street to 54th Street.

This zone has been subdivided into two sub-zones, namely, the East Zone and West Zone due to the presence of a fault on the west side of the alignment, which does not appear to intersect the alignment.

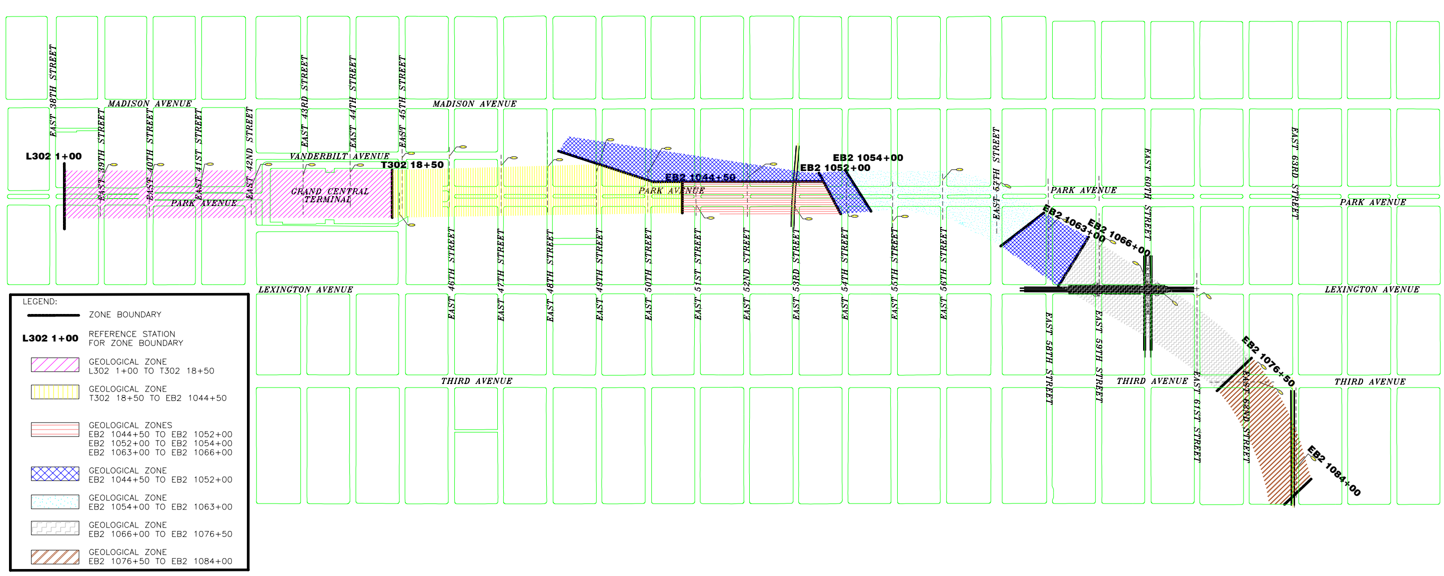

Fig 5. Rock Zones along the ESA Alignment

East zone. This zone comprises garnetiferous schist, gneiss and granofels and a major 10-foot to 15-foot thick pegmatite dipping parallel to foliation to the west across Park Avenue from East 52nd to East 56th Streets.

In general the rock mass is high quality, with few open, infilled and slickensided fractures. There are occasional micro shears and joint weathering. The joints are closely to moderately spaced with distinct sub domains of lower quality rock, characterized by clusters of very closely spaced fractures and persistent steep infilled fractures.

West zone. This is a zone of brecciated and heavily fractured rock interpreted to be a fault due to an identifiable displacement of the 10 to 15 feet thick pegmatite layer present in this area. The zone trends NW or NE between East 51st and 52nd Streets. Evidence of faulting has been found in borings from rock surface to below tunnel invert along the west of Park Avenue but not to the east of Park Avenue. The interpreted location of the fault and the predicted eastern boundary of the zone of influence of the fault are shown in Figure 5. The zone comprises fragmented rock with slickensided joint surfaces, healed joints and mineralization. The healed fractures in the pegmatite have an aperture greater than 1/16", and are susceptible to being refractured.

Park Avenue between 45th Street to 51st Street (GCT)

The rock types beneath the existing Grand Central Terminal are dominantly garnetiferous schistose gneiss and gneiss. The rock mass is typically competent, with 50% of the rock mass comprising moderately to very widely spaced foliation fractures and widely spaced joints, quartz, feldspar, and pegmatite veins in clusters with few infilled joints. The remaining 50% of the rock mass comprises closely to moderately spaced foliation fractures and joints with frequent thin to very thin pegmatite and quartz veins and few infilled joints.

The top 1.5 feet to 5 feet of the rock immediately under the GCT is fractured with RQD's tending to 75% to 80% (in comparison, the rock underlying the fractured top of rock is typically 90% to 100%). This is possibly due to the blasting effects of the construction of the GCT terminal itself and the excavations for the building footings in the area.

Park Avenue between 38th Street to 45th Street.

The dominant rock types are garnetiferous schistose gneiss and gneiss with widely spaced thin quartz, feldspar and pegmatite veins. The rock mass comprises moderately to very widely spaced foliation fractures and widely spaced joints, with widely spaced clusters of very closely to closely spaced joints.

ROCK MASS ENGINEERING PROPERTIES

Table 2 presents a summary of the engineering properties of the rock based on the various laboratory tests conducted during the course of the geotechnical investigation. The properties shown on Table 2 represent the full range of observed values. The properties were consistently variable across the entire alignment, precluding the need to classify them according to the rock zones defined above. These engineering properties formed the basis of design of the tunnels and caverns, evaluation of construction methods and equipment, the final liner, and stability analyses.

Table 2. Engineering Properties of Rock Based on Laboratory Tests.

Property	Failure Type	Range of Values
Density and Strength Properties		
Density (air dried)		158-184 (pcf)
Uniaxial Compressive Strength (UCS)	Structural	2751-19686 (psi)
	Non Structural	2303-28177 (psi)
Brazilian Tensile Strength (BS)	Structural	490-1764 (psi)
	Non Structural	357-2550 (psi)
Point Load Strength Index (PLSI)	Structural	71-1242 (psi)
	Non Structural	64-1281 (psi)
Elastic Properties		
Static Elastic Modulus		1567-14626 (ksi)
Dynamic Elastic Modulus		3037-10059 (ksi)
P-wave Velocity		9811-18270 ft/sec
S-wave velocity		5886-10400 ft/sec
Quartz, Garnet/Almandine, Hard Minerals and Abrasivity		
Quartz Content		10-60 (%)
Garnet/Almandine		0-10 (%)
Hard Mineral Content*		1-8 (%)
Cerchar Abrasivity Index (CAI)		2.7-5.2
TBM Performance Indices		
Drilling Rate Index (DRI)		48-58
Bit Wear Index (BWI)		30-42
Cutter Life Index (CLI)		5-21.5

* Minerals with Mohs' Hardness equal to or greater than 7 excluding quartz, garnet/almandine

HYDROGEOLOGY – GROUNDWATER CONDITIONS

Numerous groundwater monitoring wells were installed during the geotechnical investigation in selected locations. Measured groundwater levels range from 4.5 m below the street level along Park Avenue to less than 1.5 m below the invert of the existing lower level of GCT. Rock permeabilities were determined from in-situ packer tests and vary from 10-7 m/sec to 10-4 m/sec.

As Manhattan area is heavily urbanized, infiltration of rainfall is likely to be low. More intensive conductive fracturing will occur at the locations of the buried streams channels and shear zones previously discussed. These locations could be potential conduits for groundwater, with much greater hydraulic conductivity than other fractures in the undisturbed rock mass. Routine probe hole drilling ahead of the excavation face can be used to detect permeable zones. Grouting or temporary drainage lines may be necessary at buried streams or in areas of fractured rock where water inflow is expected to be high.

CONCLUSIONS

The comprehensive site investigation comprising archive searches, rock exposure mapping, geophysical surveys, test borings in soil and rock, oriented core readings, and in-situ and laboratory testing have been interpreted to provide a geological model for the Manhattan Segment of the ESA project. The structure was found to be complex, with regions of significant faulting, shearing, alteration and folding, particularly in the area of 58th Street between Park Avenue and 2nd Avenue. The general structure defined by the orientation of the foliation fractures indicates a change in dip direction from west along Park Avenue to the east at Second Avenue.

This investigation provided an updated and comprehensive record of the discontinuity system in the East Side of Midtown Manhattan. The data was interpreted and expected excavation conditions with due regard to construction methods are being developed. It also provided necessary data needed for the ongoing analysis and design of the various caverns, tunnels and shafts, and preparation of bid documents for this very complex project through one of the most developed and complex urban settings in the USA.

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